Contemporary Lake Superior Ice Cover Climatology

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Introduction

A brief discussion of Lake Superior ice cover climatology (Phillips, 1978) was included in an issue of the *Journal of Great Lakes Research* dedicated to the Limnology of Lake Superior (Munawar, 1978) almost three decades ago. Much additional information (and analysis) of Great Lakes ice cover has been collected (and published) since then. The objective here is to describe Lake Superior's contemporary ice cover climatology given additional information and publications since Phillips (1978).

The annual cycle of ice formation and loss on Lake Superior affects physical processes in and on the lake (Croley and Assel, 1994; Schertzer, 1978) and in the adjacent atmospheric boundary layer (Norton and Bolsenga, 1993; Eichenlaub, 1979) and thus the economy of the Great Lakes region and the ecology of the Great Lakes. Lake ice is an index of winter regional climate and climate

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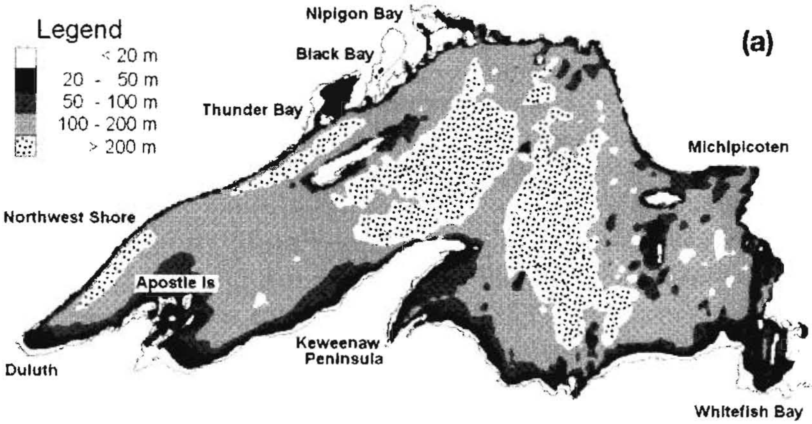
change (Assel and Robertson, 1995; Magnuson et al., 2000). The timing and extent of ice formation affects the flora and fauna of the winter lake ecosystem (e.g., Vanderploeg et al., 1992; Brown et al., 1993; Magnuson et al., 1997; Assel, 1999) as well as the regional economy (Niimi, 1982). Anomalous contemporary Great Lakes ice cycles have been documented in earlier studies (Quinn et al., 1978; Assel et al., 1985; Assel and Norton 1991; Assel et al., 1996; Assel et al., 2000). Empirical freezing degree-day models were developed to simulate past ice cover (Assel, 1990) and potential future ice cover under GCM modeled greenhouse-warming scenarios (Assel 1991; Lofgren et al., 2002). Other studies have identified Great Lakes ice cover and winter severity anomalies associated with large scale atmospheric circulation patterns (Rodionov et al., 2001; Rodionov and Assel, 2000). Recently, over 1200 historical ice charts (from 1973 to 2002) were digitized and analyzed to produce ice charts that portray spatial patterns of dates of first ice, last ice, ice duration, computer animations of the daily progression of ice cover for each winter, weekly statistics on the spatial distribution patterns of Great Lakes ice cover concentration, and daily lake-averaged ice cover for each winter (Assel, 2003a). The contemporary ice cover climatology for Lake Superior ice cycles is reviewed within the context of lake bathymetry. Long-term averages of date of first ice, date of last ice, and ice duration are presented. The seasonal progression of lake-averaged ice cover for discrete depth ranges and the spatial patterns of ice cover for early, mid, and late winter and for early spring for mild, typical, and severe winters are described and discussed. Results of a study on expected ice cover over the rest of the 21st century under two greenhouse warming scenarios are discussed briefly.

Dates of first ice, last ice, and ice duration

Lake bathymetry (Fig. 1a) and winter air temperatures (Fig. 1b) influence the severity of Great Lakes ice cycles (Assel et al., 2003). Assel (2003b) divided Lake Superior into five discrete depth ranges, $\leq$ 20 m, 21-50 m, 51-100 m, 101-200 m, and > 200 m in his analysis of dates of first ice, last ice, and ice duration. The first three of these depth ranges are located primarily along the lake perimeter and are shore or near shore environments, while the last two depth ranges



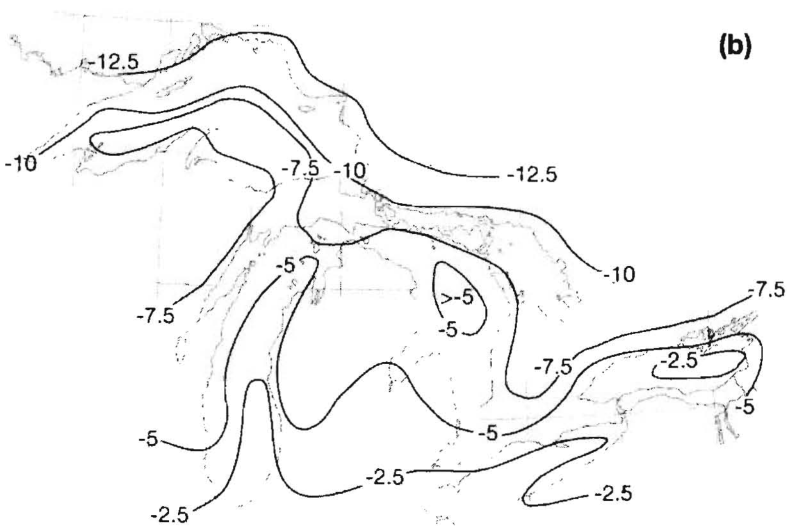


Fig 1a. Lake bathymetry and place names.
Fig 1b. Average air temperature (^{0}C) pattern over the Great Lakes region in February.

are open lake environments. The shore and near shore environments make up about 29% of the lakes surface and the open lake environment about 71% of the lakes surface. The dates of first/last ice and ice duration given below are for ice concentration ≥ 10%. See Assel (2003b) for detailed data and similar statistics for ice concentration ≥ 90%. The significance of the ≥ 10% threshold value is that it marks the boundary between ice cover and open water. The significance of the ≥ 90% threshold is that it is the upper limit of ice cover.

The average dates of first ice occurs in December in the shallowest depths (≤ 20 m), in January for the deeper and more exposed near shore areas, and in February and March in the mid-lake areas (Fig. 2a). The earliest spatial average date of first ice for the shore (≤ 20 m) and mid-lake (101-200 m) environments was December 18, 1990 and January 10 1977, respectively; latest date of first ice for shore and mid-lake environments were January 15, 2002 and February 28, 2001, respectively. The 30-year average is January 2 and February 4 for shore and mid-lake environments, respectively.

The average date of last ice cover is in March for most of Lake Superior (Fig. 2b). The average date is in April in the three large bays along the north shore, along the entire southern shore, and northward and lakeward of the east end of the lake. The latest and earliest spatial average date of last ice was May 8, 1996 and March 5,1987 for the shore environment (≤ 20 m depths); and April 19, 1979 and February 4, 1998 for the mid-lake environment (101-200 m depths). The 30-year average is April 6 and March 19 for shore and mid-lake, respectively.

The long-term average ice cover duration (Fig. 2c) is shortest (15-45 days) for a mid-lake area of the eastern lake basin and a smaller area lakeward of the northwest shore of the west lake basin. Mid- lake ice duration shoreward of these areas is 45-60 days, and shoreward of that, 60-90 days. Average ice duration is greatest (90-135 days) in the bays noted above for earliest first ice and latest last ice. Longest and shortest spatial averaged ice duration for the shore environment is 134 days (1996) and 50 days (1987); longest and shortest spatial averaged ice duration for the mid-lake environment is 89 days (1979) and 7 days (1987). The 30-year average is 96 days and 44 days for shore and mid-lake environments, respectively. Additional details can be found in Assel (2003b).

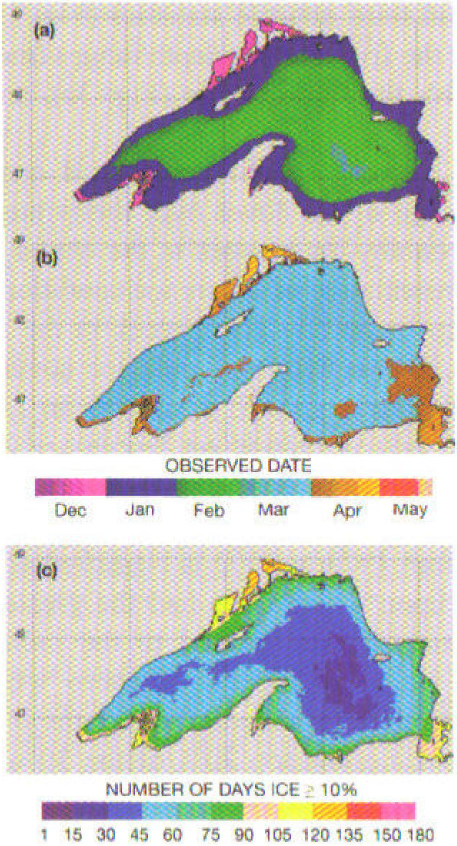


Fig 2. The 30-winter average: a) date of first ice ≥ 10%, b) date of last ice ≥ 10%, and c) ice duration (days) for ice concentration ≥ 10% (after Assel 2003a).

Temporal and spatial variations of seasonal ice cover

Seasonal lake-averaged ice concentration is examined through an analysis of overlapping weekly statistical ice cover grids given in Assel (2003a). Assel aggregated over 1200 original ice chart observation grids of total ice concentration into 173 overlapping weekly grids, e.g. week 1 is Dec. 1-7, week 2 is Dec. 2-8, week 3 is Dec. 3-9 and so on. Statistics were calculated (including first quartile, median, and third quartile) for each grid cell for each of the 173 over lapping weekly grids. A summary of these data is given here as the lake-averaged values of the over lapping weekly grids of the first quartile, median, and third quartile statistics (Fig. 3a) and the lake-averaged values for the five discrete depth ranges (mentioned earlier) for median (Fig. 3b), the first quartile (Fig. 3c), and third quartile (Fig. 3d) statistics.

The ice cover between the first and third quartiles (Fig. 3a) defines a typical range of ice cover over the winter season. Lake-averaged ice cover on any given week in the winter greater than the third quartile is representative of severe ice conditions for that week, lake-averaged ice cover on any given week in the winter less than the first quartile is representative of mild ice cover for that week, where the week of December 1-7 is plotted on December 1, the week of December 2-8, is plotted on December 2, and so on in Figures 3a-3d. Using these criteria, lake-averaged ice cover for each day during a given winter is characterized as mild, typical, or severe. Then each winter from 1973 to 2002 is classified as severe, typical, or mild depending upon which class had the greatest frequency of occurrence. This analysis was limited to the months of January, February, March, and April because there were insufficient observations most winters to include the months of December and May. The six winters, i.e. the top 20% of the 30 winters, with the greatest number of severe days during these four months are: 1977 (107 days), 1979 (99 days), 1994 (90 days), 1996 (65 days), 1974 (59 days), and 1984 (51 days). In a similar fashion, the six winters with the greatest number of mild days are: 1998 (107 days), 2000 (90 days), 2002 (72 days), 1987 (67 days), 1999 (67 days), and 1995 (48 days). These then are the extreme winters for Lake Superior over the 30 winters under study. Thus, there is a definite bias for milder winters since the late 1990s, four of the six mildest winters occurred since 1998. The six severe winters are more evenly spread over the 30-winter study period.

The ideal annual ice cycle consists of a period of increasing ice extent, leading to seasonal maximum ice extent, followed by a period of decreasing ice extent, leading to loss of all ice cover. In general, the month of greatest increase in ice extent is the month of January for the shallower portions of the lake (the 0-20 m, 21-50 m, and 51-100 m lake depths), and February for the deeper lake portions (101-200 m and > 200 m lake depths), Figs. 3a-3d. Exceptions occur for the third quartile (Fig. 3d) for which the greatest increase in ice extent is a month earlier for the shallowest depths (December for 0-

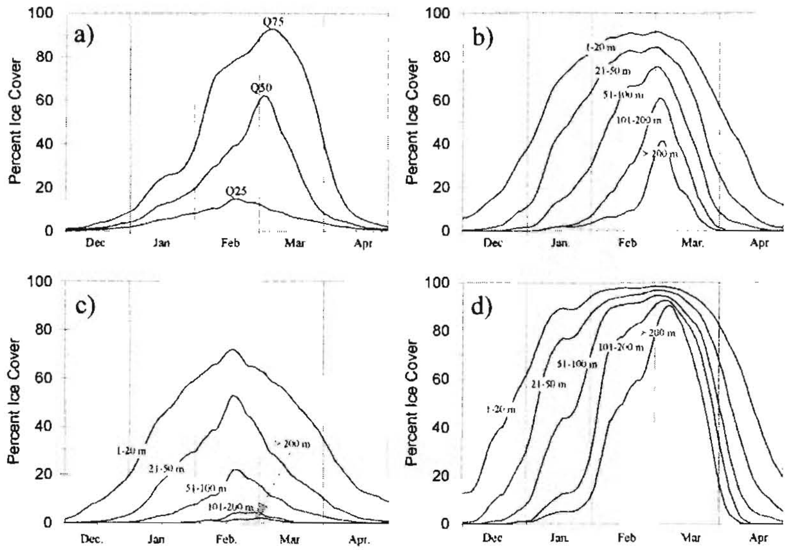


Fig 3. Lake-averaged ice cover a) for first quartile (Q25, mild winter), median (Q50, typical winter), and third quartile (Q75, severe winter) of the cumulative frequency distribution. The spatial average ice cover statistics of: b) median, c) first quartile, and d) third quartile for lake surface areas corresponding to five discrete depth ranges. Statistics based on overlapping weekly ice cover grid statistics given in Assel (2003a). All curves smoothed by a 7-day moving average.

20 m) and the next to deepest depth range (January for the 101-200 m depths); and the first quartile (Fig. 3c) for which the greatest increase in monthly ice extent is a month later (February) for the 51-100 m depths. The period of maximum ice extent has its greatest duration and amount for the shallowest lake depths (0-20 m, Figs. 3b-3d, Table 1) and decreases in amount and or duration from the shallowest to deepest depth ranges, from the third quartile to first quartile (Table 1). In general the period of maximum ice extent ends in early to mid March, and the greatest loss in ice extent occurs during that month for all five discrete lake depth ranges. For first quartile ice cover (representative of mild winters), the date of maximum ice extent occurs in February (Fig. 3c), and the difference in spatial averaged ice cover between the 0-20 m and > 200 m layer

is 58%, because mid-lake areas are virtually ice free. While for median ice cover (Fig. 3b), the date of maximum ice extent is in early March, and the difference between the 0-20 m and > 200 m spatial averaged ice cover decreases to 40%, because the ice cover in the 100-200 m and > 200 m layer is greater relative to the first quartile values. Maximum ice cover for the third quartile (Fig. 3d), representative of a severe winter, occurs in early to mid March; it starts earlier for the shallower lake depths (0 – 20 m), and the difference between the 0 – 20 m and > 200 m layer in the first week of March is at a minimum (about 10%), because even the deepest areas of the lake are approaching a complete ice cover. Ice extent in early April is largest for a severe winter (Fig. 3d) and smallest for a mild winter (Fig. 3c), providing significantly different early spring conditions for the flora and fauna of Lake Superior.

The amount and location of ice cover during early winter (1-7 January), mid winter (1-7 February), late winter (1-7 March), and early spring (1-7 April) for first quartile (mild), median (typical), and third quartile (severe) ice cover are portrayed in Figs 4a-4l. Mild winters are illustrated by the first quartile ice charts (Figs. 4a, 4d, 4g, and 4j). Ice is limited primarily to the three large bays along the north central shore and the Apostle Islands the first week of January. By mid-winter (February 1-7), ice also lines the south shore of the lake in water depths of 50 m including the Apostle Islands and Whitefish Bay. By the first week of March, ice cover also includes the south half of the east shore of the lake to Michipicotin Island. By the first week in April, the main body of ice has receded to the three large bays along the north shore, the Apostle Islands, and Whitefish Bay.

Spatial patterns for a typical winter ice cover are shown in Figs. 4b, 4e, 4h, and 4k. Early winter ice cover (Fig. 4b) is a little more extensive but similar in extent to the mild winter (Fig. 4a). Mid-winter ice cover (Fig. 4e) lines the entire shore of the lake, water depths of 21-50 m, and 51-100 m have average ice cover of 73% and 40% respectively. The lake is near its seasonal maximum ice cover the first week of March (Table 1, Fig. 4h). Spatial average ice cover for the 0-20 m, 21-50 m, 51-100m, 101-200 m, and > 200 m lake depths are 91%, 83%, 73%, 59%, and 40%, respectively. The only large area of open water is in the eastern lake basin, approximately in a rectangle bounded by 48°N - 47°N and 87°W - 86°W. Areas of low ice concentration occur to the northwest of the

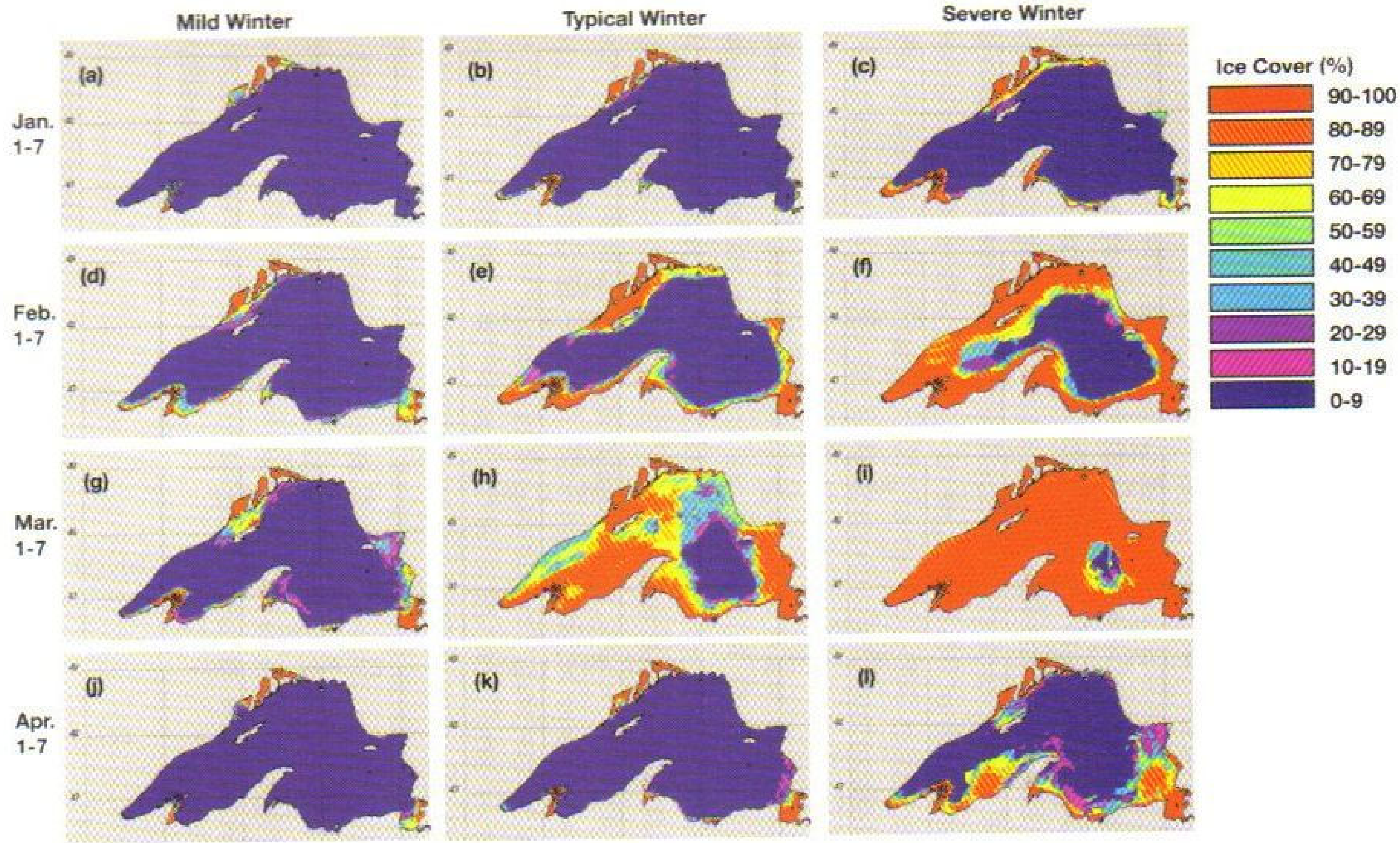


Fig 4. Lake Superior ice cover for early winter [Jan 1-7: a), b), c)], mid winter [Feb. 1-7: d), e), f)], late winter [Mar. 1-7; g), h), i)], and early spring [April 1-7: j), k), l)], for mild [first quartile: a), d), g), j)], typical [median: b), e), h), k)], and severe [third quartile: c), f), i), l)] winters, from Assel (2003a).

Table 1. Maximum ice cover for five discrete depth ranges and for severe, typical, and mild winters, as represented by the third (Q75), median (Q50), and first (Q25) quartiles of the cumulative frequency distribution of daily lake-averaged ice cover, respectively.

	Depth Ranges				
	0-20 m	21 - 50 m	51 - 100 m	101 - 200 m	> 200 m
Severe Winter (Q75)					
Dates	Jan 24 Mar 22	Feb 1 Mar 15	Feb 8 Mar 9	Feb 27 Mar 9	Mar 4 Mar 9
Ice Cover	≥ 90%	≥ 90%	≥ 90%	≥ 90%	≥ 90%
Typical Winter (Q50)					
Dates	Feb 1 Mar 13	Feb 2 Mar 10	Feb 12 Mar 7	Feb 27 Mar 6	Mar 2 Mar 3
Ice Cover	≥ 85%	≥ 75%	≥ 65%	≥ 55%	≥ 45%
Mild Winter (Q25)					
Dates	Feb 1 Mar 1	Feb 8 Feb 27	Feb 12 Feb 28	Feb 14 Mar 1	Feb 25 Mar 1
Ice Cover	≥ 60%	≥ 40%	≥ 15%	≥ 3%	≥ 2%

open water and along the northwest shore of the lake where water depths exceed 200 meters and off shore winds (i.e. winds from the northwest) can cause upwelling of warmer waters. A month later (April 1-7), early spring ice extent has decreased substantially, remaining ice covers are once more limited to the three large bays along the north central shore and large bays and shoals along the south shore. In early April, lake depths of 0-20 m average 49%, 21-50 m average 19%, and 51-100 m average 5% ice cover. Mid-lake areas are ice-free.

Spatial ice cover patterns for a severe winter are portrayed in Figs. 4c, 4f, 4i, and 4l. Early winter ice cover is substantially greater in the shore region relative to the typical (median) and mild (first quartile); mid-lake areas are still ice free. By mid-winter, Feb 1-7, ice covers virtually 100% in the 0-20 m and 21-50 m depth ranges, over 80% in the 51-100 m range, 50% in the 101-200 m range, and 20% in lake depths over 200 m. Low ice concentration extends from the deep waters off the northwest shore and northwest of the Keweenaw Peninsula and lead to a large area of open water in the eastern lake basin. These areas are among the deepest of the lake (Fig. 1a). In late winter (March 1-7), the lake is near its annual maximum ice extent, and ice cover is over 95% in lake waters less than 100 m, over 90% in the 101-200 m depth range, and over 80% in depths over 200 m (Fig. 3b, Fig 4i). The only area of open water and low ice concentration is located in the southwest quadrant of a rectangle bounded by 48°N - 47°N and 87°W - 86°W. There is a dramatic decline in mid-lake ice cover over the next month. By the week of April 1-7, the spatial average ice cover of lake depths over 200 m is 5%, for lake depths between 101-200 m it is 19%, for depths between 51-100 m it is 36%, for depths between 21-50 m it is 58%, and 77% for depths up to 20 m. The bulk of the mid-lake ice cover is located lakeward of the southern lakeshores and lakeward of the southeast end of the lake.

Ice thickness

The maximum ice thickness formed from the direct freezing of lake waters under the climate of the past 30 winters is approximately 100 cm for shallow protected areas of bays and harbors. Bolsenga et al.,

(1988) report the average freeze-up date for bays and harbors in Lake Superior occurs the last week in December, the average date of maximum thickness occurs the second week of March, the average maximum thickness is 53 cm, and the average break-up date occurs during the second week in April. Ice formed from the direct freezing of lake waters in mid-lake areas does not exceed the thickness of ice formed in bays and harbors. However, thermal expansion and winds can cause ridging and rafting of ice covers that result in thicknesses of one to several meters in depths (Marshall, 1977). Constricted locations such as Whitefish Bay, the lake west of the Apostle Islands, and other bays along the southern shore are susceptible to ice ridging with the occurrence of high on-shore winds in the presence of an off shore ice field.

Potential ice cover under greenhouse warming scenarios

In a recent study (Lofgren et al., 2002) freezing degree-day ice cover models were used to estimate ice cover under greenhouse warming scenarios generated by the Canadian Centre for Climate Modelling and Analysis general circulation model [CGCM] and the Hadley Center for Climate Prediction and Research model [HadGCM] general circulation model. Simulations of average ice cover were made for three 20-winter periods centered on the years 2030, 2050, and 2090. Based on the CGCM and the (HadGCM) scenarios, the duration of ice cover averaged 82 (96), 67 (90), and 30 (67) days for mid-lake basins and 91 (103), 77 (99), and 40 (77) days for a large bay, i.e., Whitefish Bay. The current median lake averaged ice duration [1973-2002] for ice cover ≥ 10% is 91 days. That study also indicates that winters without ice cover would occur 4% for Whitefish Bay (CGCM) to 36% for mid-lake areas (HadGCM) of the time during the last two decades of this century. The differences in the magnitude of decline in ice cover duration and extent due to differences in the CGCM and the HadGCM scenarios provide a degree of uncertainty in projected ice cover over the century ahead. Given this caveat, a reduction in ice cover would occur as part of an alteration of the onset of spring warming, summer stratification, and fall overturn in Lake Superior. Such a change in the thermal regime of the Great Lakes would have implications for the aquatic system, lake-effect processes, and the regional economy (Brandt et al., 2002; Magnuson et al., 1997; Sousounis and Bisanz, 2000).

Conclusions

The spatial pattern of initial ice formation on Lake Superior is related to its bathymetry (Fig. 1a). Ice forms in the shallows of Lake Superior in December, in the more exposed shore areas in January, and in mid-lake areas in February (Fig. 2a). Ice can form in mid-lake in January in a severe winter (Assel et al., 1996) or not form at all in a mild winter (Assel et al., 2000). Ice loss usually occurs during March in mid-lake areas and in April in shallow shore areas (Fig. 2b). In spring, substantial ice cover can last in mid-lake and shore areas into May as it did in 1979 and 1996 (Assel, 2003a; 2003b). The duration of ice cover is longest in the shallow lake areas, typically from December to April (Fig 2c). Ice duration in mid-lake areas is typically on the order of two months (February and March) (Figs 2a-c, Fig 3b), it can last longer in severe winters (Fig. 3d), or mid-lake areas can remain ice free in mild winters (Fig. 3c). The winters of 1977, 1979, 1994, 1996, and 1974 were among the most severe, and the winters of 1998, 2000, 2002, 1987, 1999, and 1995 were among the mildest over the 30-winters under study. During severe winters, seasonal maximum ice cover is 90% or greater over the entire lake. During mild winters spatial average for shallow depths (0-20 m) is 60% or greater, and for deeper depths (101-200 m) it is 3% or greater (Table 1). Global warming scenarios imply that the ice cover by the end of this century will be similar to or less than mild winters of the present ice cover regime. This will have a significant impact on the aquatic ecosystem (e.g. Great Lakes fishery) as well as the regional economy (e.g. winter navigation, lake-effect snow fall).

Summary

A thirty-winter (1973-2002) Great Lakes ice atlas and related publications are used for an analysis of Lake Superior ice cover. Dates of first ice, last ice, ice duration, and ice cover spatial averages and spatial patterns are analyzed within the context of lake bathymetric

ranges. Results are summarized in a table, line graphs, and ice charts. Severe (mild) winters are identified based on the number of days each winter that the lake-averaged ice cover was above (below) the third (first) quartile of the 30-winter smoothed daily lake-average. Ice charts portray the spatial distribution patterns of ice cover concentrations for early, mid, and late winter and early spring for mild, typical, and severe winters. A study of the impact of global warming on the Great Lakes indicates that typical ice cover near the end of this century may be similar to mild winters described here. Such a change in the ice cover regime would impact the lake aquatic system and the regional economy.

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State of Lake Superior

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